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 ENERGY-EFFICIENT SOLUTION TO THE  
 AIRPORT CONGESTION PROBLEM

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THE AERIAL RELAY SYSTEM:  
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Summary

The ability to transfer airline passengers between aircraft in flight, if adequately developed and integrated into the national air-transportation system, could provide significant improvements in transportation-system performance, in terms of airport congestion, fuel consumption, and passenger service. The proposed Aerial Relay System concept, which was developed as a means of exploiting inflight transfer, makes use of large "cruise liner" aircraft which fly continuously along their routes, docking periodically with short-haul "feeder" aircraft for exchange of payloads. The paper describes preliminary vehicle designs for a "representative" system, and discusses the operational feasibility of the concept for the United States in the 1990's.

Introduction

The air transportation industry of today seems to be remarkably indifferent to the problem of the capacity of the airport system and its effect on the long-term viability of air transportation as we know it. The result of this indifference is that air transportation in the United States appears to be approaching the end of an era: unless sweeping changes are made in the manner in which traffic is handled at the major metropolitan airports, or unless the growth in demand decreases drastically, within a few years the system will be unable to satisfy the unconstrained free-market demand.

The limited capacity of the airport system has been evident for perhaps two decades, but it is now becoming more critical than ever, because of the uniquely severe impact of the various socioeconomic trends which have distinguished the decade of the 1970's: the energy crisis, which not only threatens air transportation because of the scarcity and cost of petroleum, but which also inhibits expansion of the airport system by depleting the nation's resources of investment capital; the general inflation in the cost of acquiring real estate and constructing new facilities; and the new environmental awareness, which has catalyzed civic opposition to the construction of new airport facilities and the expansion of existing facilities. These factors weigh heavily against the likelihood of a major program of airport expansion in the next decade, as would be required to match the continuing rapid rise in demand.

If the air transportation system is to continue to grow in the absence of a program of air-

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port expansion, it seems apparent that some means must be found to relieve the traffic load at the metropolitan terminals. The Aerial Relay System concept which is described here is proposed as one means of relief. The concept would permit the heavy flow of metropolitan and regional traffic, which today must pass through the terminal, to remain diffused throughout the areas where it is generated. The freedom to operate without concentrating the traffic is achieved by performing many of the terminal functions in the air aboard special-purpose Relay-System aircraft. In this sense, then, the proposed Aerial Relay System is a "flying airport" concept.

In order to motivate this unconventional concept and to improve the understanding of its potential contribution to the relief of the airport congestion problem, it is useful to review the manner in which the air-transportation system in this country originally developed. The following background section presents a brief history of the air transportation system, and discusses the need for over-hauling the existing system in order to meet the expected rise in airline-traffic demand for the next few decades.

Background

The Development of the Existing System

The airline system in the United States began about 1925, when the Congress moved to support the infant commercial-aviation industry. One act of Congress was to direct the Federal Government to relinquish the highly publicized and successful Postal Service airmail operation in order to promote the development of scheduled airline traffic; another act provided for the establishment of safe "airways". With the assurance of profitable airmail payloads, and with the safety of Federally maintained navigation routes and landing fields, the airlines were encouraged to establish scheduled service along existing airmail routes. In 1926, the existing route network could provide airline service coast-to-coast, from New York to Los Angeles, by way of a thirty-hour succession of city-to-city hops, as shown in Figure 1 (Ref. 1). Once established in this manner, the air transportation industry grew rapidly, and within a few years had become an essential element of the national transportation industry. After the initial starting transient, airline traffic grew by a factor of ten per decade (about 25 percent per year) throughout the 1930's and 1940's (Ref. 2).

A major ingredient in the rapid growth of air transportation was the fact that the cost of going into business was extremely small by comparison

with other modes of the day. The prestige and glamour associated with air travel was enough to induce civic leaders in every community of any size to promote the acquisition of an airport by which the community could be connected to the growing airline route network; local airports were a source of civic pride as well as business opportunity and the public supported their development. Once the airport was established and operating, the Federal Government provided the support necessary to assure that safe operating conditions were maintained. The prospective airline operator, in order to enter the business, simply had to provide an airplane and hire a pilot. There were no roadways to acquire and maintain, and there were no long lists of municipalities to whom property taxes had to be paid, as was the case for the railroads. This remarkable business opportunity provided a steady flow of capital for airport and airline investment, in spite of the serious economic difficulties of the nation as a whole during those depression years.

By the mid-1950's, the airline route system had become sufficiently well developed and complex that the need to provide connecting flights for the large number of city pairs had become a major problem in airline operation. The airlines responded to this need by establishing the regional hub-and-spoke system, by which essentially all passengers traveling in or out of a large, loosely defined region would be routed through the hub airport, where connecting flights were most likely to be available by virtue of the concentration of traffic at the hub. The hub-and-spoke concept thus became the basis for the future development of the national air transportation system.

When the jet transport became available, in the late 1950's, the industry was faced with the need to retire a large fleet of nearly new reciprocating-engine transports in order to take advantage of the newer jet propulsion. The investment in jet transports paid large dividends because of increased productivity and decreased maintenance costs. Furthermore, the early concerns about passenger acceptance were replaced by the need to impose a surcharge on the jet fare, to protect operators who had not yet replaced their propeller equipment. The fact that these new transports were externally noisy, dirty, and energy-inefficient bothered no one except that portion of the public who did not fly.

By the late 1960's the national air transportation route network had become well established essentially in its present form, which is depicted in Figure 2 (Ref. 1). The airline system utilized some two thousand transport aircraft to provide service to several hundred communities throughout the nation, making it possible to travel by air, through the hub-and-spoke system, between tens of thousands of city pairs. Traffic was continuing to grow at rates approaching ten percent per year, and the introduction of the widebody transports promised a continuing evolution of ever-improving airline service.

Meanwhile, back at the airport, the mood was considerably less optimistic. The metropolitan airports, which also served as regional hub terminals, were becoming seriously congested. With the advent of the environmental movement, the community's perception of the unblemished value of

air transportation had changed to the extent that it had become almost impossible to increase the capacity of the airport system to accommodate the rising demand. The change in attitude is easily understood, since the airports which the system needs are large regional hub terminals, not local airports serving local communities. People living in the neighborhood of a regional terminal feel no sense of community spirit toward the service it performs, and resent its dominating presence. Thus, by the mid-1960's, the airport system had almost ceased to expand, and the increase in traffic began to depend more than ever on the increasing size of transport aircraft.

The brief respite in the rising demand which resulted from the temporary slump of the early 1970's, and which happened to coincide with the introduction of the widebodies, only served to turn the "temporary" shortage of airport capacity into a permanent shortage. By the time the rising demand had taken up the slack introduced by the widebodies, and had thereby brought the airport-capacity problem back into focus, the prospects of finding a solution had practically vanished: the petroleum crisis had become established, prices of real estate and construction had increased beyond reason, the environmental movement had strengthened, and the national mood toward technological expansion was changing rapidly. At the present time there is essentially no more airport capacity in the major metropolitan areas than there was in the mid-1960's, although some expansion of the overall capacity of the system has occurred through the establishing and/or enlargement of several "way-station" terminals (Atlanta, Dallas/Fort Worth, Denver) which serve to remove some of the transfer-traffic load from the primary hub terminals in the largest metropolitan areas.

During the past two years the system has been adjusting to the effects of airline deregulation, which has brought competition, fare decreases, and a rise in the rate of growth of air travel to about sixteen percent per year. Deregulation has also produced a sudden and distinct deterioration of service to smaller cities, as the airlines moved their equipment to more lucrative routes. The void in the market for service to smaller cities has, in turn, produced a sudden influx of smaller transports, which are now contributing disproportionately to the congestion at the major terminals; small transports absorb operation "slots" that could be filled by larger aircraft. Thus the effect of deregulation, at least up to the present time, has been both to increase traffic and to decrease capacity at the major terminals, while decreasing the level of service to smaller airports.

As the air transportation system now stands, then, it is experiencing a period of rapid growth of demand, with an airport system which has barely enough capacity for the current traffic, and with no real hope of being able to expand fast enough to keep abreast of the capacity. This is the result of a history of rapid, unstructured growth in which each new development has been undertaken in the spirit of enlarging or refining the system in existence at the time, and in which most of the development has been privately financed and therefore motivated by short-term business interests. The system which has evolved is now carrying about ten times as much traffic as

it was originally set up to carry, and as a result the critical hub terminals are saturated at every level: ground access, terminal facilities, ramps, runways, and terminal-area airspace. It seems apparent that if the air transportation industry is to grow much beyond its present size, some drastic overhauling will be required.

### The Need for a New System

The Aerial Relay system concept represents a radical departure from convention, and therefore its implementation would require (and/or permit) some major changes of habit within the air transportation industry. Since any proposal to make substantial changes in a well-established, mature industry requires considerable justification if the proposal is to serve its intended function, it is believed to be worthwhile here to devote the space required to develop the necessary justification. This section is intended to provide the justification by setting down the basis for the claim that the existing air transportation system may not be suitable for the 1990's, and then by indicating the nature of changes which are believed to be required if air transportation is to be able to satisfy the demand projected for that period.

It has been shown that the present shortage of airport capacity is the result of a history of rapidly increasing demand for air travel, with essentially no program of expansion of the airport system to maintain the reserve capacity. The failure to undertake such a program, as well as the widespread systematic problems which have resulted, can be attributed to a fundamental cause: the architecture of the existing air transportation system is intended to attract traffic to the large metropolitan-area terminals. A central feature of the system design is the regional hub-and-spoke airport system, which serves the fundamental transportation-system function of "mixing" the passenger trip-paths, so as to provide the necessary origin-destination versatility. The regional hubs were originally established at the large metropolitan airports because of the need to take advantage of the large pool of metropolitan-area traffic to facilitate the mixing. The hubs have always been operated with as much traffic as possible, because in that way the system becomes most effective in "pooling" flights so as to improve the system performance in general: high concentrations of traffic produce better load factors for the airlines, better service to the passengers, and better business for the airport. The motivation to expand the airport system in order to diffuse the extraordinary concentration of airline traffic at the hubs has thus been lacking, and the airport system finds itself at the present time poorly suited to handle the rapidly increasing demand.

An indication of the seriousness of the capacity problem is diagrammed in Figure 3, which shows some predictions for the growth of demand for domestic revenue traffic in the U. S. for the next two decades. The shaded region indicates the approximate range of projections that one can find in the literature. The lower bound (three percent per year) represents a very conservative estimate; nevertheless it predicts a doubling by the year 2000. The more optimistic projections such as those shown by the upper two curves (which were

taken from Ref. 3) predict a much more rapid rise in demand. The 8.7 percent curve, which was derived assuming constant real fare, indicates a factor of five by the year 2000; if it is assumed that the fare is reduced by thirty percent, the demand-growth prediction suggests a factor of ten over the present-day full-fare traffic.

It is interesting to consider the implications of this projected growth of demand. If traffic were to triple, there would be about twenty airports in the United States with origin-destination traffic greater than Los Angeles has at the present time (Ref. 4). This kind of expansion is hard to imagine, especially in view of the fact that about fifteen of the largest airports in the United States are now operating on a "quota" basis, which means that they are turning away business. Furthermore, the number of quota airports has been increasing steadily for the past decade or so.

The urgency of the problem can also be observed in the tight schedules on which the large airports are currently operating. According to ATA data (Ref. 5) for August 1976, the twenty-four-hour average traffic on a typical day at both the Chicago O'Hare and the Los Angeles International Airports was about fifty-five percent of the peak-hour traffic; excluding the week-hour slack period, the average was about seventy-five percent of the peak (it was ninety percent at Washington National). If it can be assumed that the traffic density during the peak hour at these busy airports is about as great as the airport and airline operators dare to schedule, then these major airports, and many others as well, are obviously uncomfortably close to their present ultimate capacities. It therefore seems doubtful that the capacity can be made available to meet a tripling of demand within the next two decades without a major program of airport expansion.

On the other hand, the prospects of expanding the airport system to meet a tripling of demand seem very remote indeed. The Dallas-Fort Worth airport, which was completed in the early seventies, is said to have cost about a billion dollars. Using that figure as a basis, it seems safe to guess that the construction of facilities to accommodate a demand of three times as much traffic as today's would involve a national commitment in excess of \$50 billion (in today's dollars). To this cost must be added the cost of expanding the aircraft fleet, which would amount to at least another \$50 billion. Such a commitment is not likely to come about in a period of rising inflation and uncertainty about energy. Even if the commitment were made, however, a large-scale program of expansion would be unlikely to be carried through, because of the widespread public opposition to the construction of new large airports.

The problem of the national air-transportation system can thus be stated very simply: the system is alarmingly short of capacity now, and from all indications it will soon be unable to satisfy the unconstrained free-market demand. Increasing the capacity adequately, if it can be done at all, will require a national commitment for support which is far greater than the support which has been required to bring the

system to its present stage. Furthermore, an extensive program of expansion of the existing system cannot provide any basic improvements in the system; the new, enlarged system will have all the inefficiencies and limitations of the existing system, including both air-side and ground-side congestion at the major hubs, excessive door-to-door trip times with unwanted stop-overs and plane changes for a large fraction of the traffic, and excessive fuel consumption compared with competing modes of transportation.

The existing system was established in the 1950's, based on technology available at that time, and was intended for traffic volumes of about ten percent of those which we have now. On the other hand, a new system which might be designed specifically for the 1990's and beyond might offer far more capacity with less congestion, more comfort and convenience, and better fuel economy because it can take advantage of some forty years of developing technology. Considering the fact that the development cost of the new system would be a very small fraction of the cost of expanding the existing system, and might in fact be saved ten times over by the improvements in the overall efficiency of the more modern system, it seems reasonable to suggest that perhaps the industry should begin to consider taking a new approach.

The study on which the present paper is based was motivated by the conviction that the existing air-transportation system is in fact becoming obsolete because of its inability to generate adequate capacity, and by the further conviction that, in a more modern context, aeronautics could do much better. The Aerial Relay System concept which has grown out of this study is offered here as one possible scheme by which the national system might be overhauled to meet this crisis of capacity.

#### The Aerial Relay System Concept

The Aerial Relay System is an advanced sub-sonic, transportation-system concept which is intended to be capable of satisfying the air transportation requirements of the 1990's. The concept has evolved to its present form as a result of a continuing effort to discover a means of using the most modern technologies to alleviate the problems of the industry. The effort was motivated by the conviction that the problems cannot be solved by simply refining the designs of conventional transport aircraft to gain ten or twenty percent in fuel economy or frequency of runway operation.

In keeping with the view that the principal need of air transportation is a large increase in the ultimate capacity of the national system, the study effort has been directed primarily toward finding a potentially workable system concept which is capable of handling the very large traffic volumes projected for the 1990's and beyond. The major assumptions which have shaped the concept are that fuel efficiency will be important, and that advanced, high-capacity, electronic subsystems will be available for the gathering, processing, and transmission of data as required for operational control of the system at all levels. A further assumption has been that, for

an advanced national air transportation system such as this, operational complexity would be acceptable if it were required for the sake of efficiency and effectiveness.

The principal distinguishing feature of the system concept under consideration here is the use of routine in-flight transfer of passengers and cargo between aircraft which are regularly scheduled to rendezvous enroute and dock temporarily for the purpose of exchanging payloads. By exploiting the capability to direct each passenger, in "relay" fashion, through a sequence of in-flight plane changes as he proceeds along his trip path, it becomes possible to configure an air-transportation system concept which appears to have the required properties:

- it would have an ultimate capacity which is many times as great as that of the existing system
- it would provide substantial improvements in fuel economy
- it would provide substantial improvements in comfort and convenience to the passenger

As will be seen, these improvements are the result of radical changes in the transportation system architecture at the most fundamental level. The changes are of a kind that depend on various high-level technologies that can reasonably be expected to be available in the decade of the 1990's. Because the new system architecture is fundamentally different, however, the Relay system is capable of being implemented at a reasonable cost, without interfering with the existing system, by exploiting existing facilities which are now under-utilized; it is also capable of being operated in a way that not only helps to unload the existing system, but actually helps it to carry the remaining traffic more effectively. The implementation would therefore immediately begin to reduce congestion in surprisingly cost-effective manner, as will be shown.

It is recognized that the matter of in-flight plane changes seems to many people to be impracticably difficult and dangerous, and is hard to imagine in the context of routine commercial operation. The possibility should not be dismissed lightly, however, because it relaxes or removes many of the most burdensome constraints in transport-aircraft design and operation. It is believed that this level of "departure from convention" should be well within the technology of the 1990's, and that the seriousness of the present system-capacity problem easily justifies the required development, if it is a necessary feature of the desired technical solution.

#### System Elements

The basic elements of the Aerial Relay System are sketched in Figure 4. The system makes use of two distinctly different kinds of aircraft, one for takeoff and landing, and one for cruise, with provisions for the routine inflight transfer of passengers, baggage, fuel, flight crews, supplies, etc., between them. The takeoff-and-landing aircraft, which are called "feeders", are relatively small, conventional, short-haul transports

which are specialized for terminal-area operations and climb; the cruise aircraft, which are called "liners", are very large flying-wing aircraft which are specialized for long-range cruise. The passengers are carried between the ground and the liners in the feeders, and make the long-distance, cruising portion of the trip in the liners. The transfer of passengers between feeder and liner takes place at the liner's cruise altitude and cruise speed, as the liner proceeds continuously along its route, without circling or loitering and with no interruption in its progress. In this way the liner can traverse the route in minimum time, while exchanging passengers with a steady succession of feeders. The docking frequency is limited only by the available docking space on the liner, and the system schedule is not penalized by including service to secondary airports which lie along the route.

The feeders operate only locally, in short hops that consist of flying from one airport to another, with a rendezvous, docking, and transfer sequence in mid-flight. Since the feeder is not normally required to cruise, it may be specialized for takeoff, climb, and landing, with little compromise to achieve high efficiency in cruise. It can have a relatively high thrust-to-weight ratio with relatively low wing-loading, large high-lift devices, and large control surfaces, to give it excellent low-speed performance near the terminal and the ability to climb rapidly to cruise altitude; it can incorporate high-quality noise treatment and "exotic" terminal-area devices such as all-weather landing systems and powered wheels, for reliable and unobtrusive operation in the terminal area. These embellishments can be incorporated at a small fraction of the cost in overall system performance which would be experienced by a conventional transport design, because of the fact that they do not affect the long-range cruise performance of the system.

Since the liner aircraft are not required to land in order to take on or discharge passengers, the liners can fly continuously day and night, for indefinite periods of time without landing. The liner design can therefore be specialized for efficient cruising flight, almost without regard for the conventional constraints of terminal-area operations. It can have a very large span, as desired for cruise, independently of runway widths; it does not need high-lift flaps, or heavy landing gear. Furthermore, the engines may also be specialized for cruise: they do not need noise suppression or thrust reversers, and the airplane does not have to meet the usual requirements for takeoff field-length or engine-out climb. The liner aircraft can therefore be relatively simple, lightweight, efficient cruising vehicles, as compared with conventional aircraft of the same speed and capacity.

In order to permit periodic ground maintenance on the liner equipment, as well as to provide an emergency-landing capability, without having to provide the means to land the very large flying wing as such, the liner is made up of a number of identical "modules", each of which is capable of flight as an independent aircraft. In operation, the liner modules fly side-by-side in a string, flexibly coupled at the wingtips to provide a high-aspect-ratio wing with continuous passenger-cabin volume (in the manner of a

passenger-train "flying sideways"). Ground maintenance can thus be performed as necessary on any given module by releasing it from the string and landing it separately. After the ground maintenance operation, the individual modules are returned to service by flying them separately to rendezvous with the liner string, and then coupling wingtip-to-wingtip in flight.

To maintain structural loads on the very long liner wings within reasonable limits, the wingtip couplings would be designed to provide angular freedom in all directions, and to release before the relative motion or the loads across the coupling became dangerous. To aid in trimming the coupled aircraft for efficient flight, the coupling mechanism would probably incorporate some capability to transmit bending moment across the coupling. The mechanism would also require a fail-safe airlock to prevent loss of cabin pressure following emergency disconnect from the adjacent module.

Since the Relay liner can remain indefinitely at cruise altitude, it can be relatively easily adapted for laminar flow control (LFC) to reduce skin-friction drag. The operation of an LFC-equipped Relay liner would not be burdened by maintenance problems associated with surface contamination by insects and dust particles, which would be encountered by conventional transports at low altitudes but which are almost nonexistent at cruise altitudes. Furthermore, the LFC system in the liner would be effective essentially full time, so that the potential for saving fuel could be an extremely important factor in the energy efficiency of the overall system.

It can be seen, then, that the use of in-flight transfer allows the Relay system aircraft to be specialized in a way that would not otherwise be useful, thereby allowing efficiencies that would not otherwise be possible. The opportunity to specialize the aircraft in these extreme ways does not come free, of course: a high price is paid in terms of operational complexity and increased dependence on an extremely high level of system reliability, including high-precision scheduling of multiple-aircraft operations. The ability to operate a commercial system on such a rigorous basis has not been demonstrated, but there appear to be no physical limitations which would preclude it, even today. Given another ten years of systems technology development, the high-precision scheduling should be a relatively straight-forward matter.

#### Basic Operation

The manner in which the Relay system might operate is indicated in Figure 5, which shows a liner route running back and forth across the United States between the population centers in the Los Angeles/San Francisco Bay area and the New York City/Boston area. The Relay liners would fly continuously along this route at cruise speed and altitude, meeting feeders at the ends of the route and at a number of cities along the route during both the eastbound and westbound portions of the round trip. The number of modules per liner, as well as the number of liners which would be used on such a route, would depend on the availability of equipment and on the demand. As an example,

however, if this route were arranged as a twelve-hour round trip, each liner on the route would make two trips per day; if the route employed, say, six liners (each with several modules), then service could be provided every two hours in both directions to each airport with appropriate feeder service.

The feeders which serve the cities along the route would fly in short hops from one city to another as they shuttle passengers to and from the liners. To examine the feeder operation, consider a westbound liner and a westbound feeder flying from city A to city B, as indicated in Figure 5. The feeder would leave city A at the appropriate time to rendezvous with the liner approximately midway between the two cities. It would takeoff, climb, and accelerate along a programmed flight path designed to bring it onto the flight path of the westbound liner at the proper time and at the proper speed for the docking maneuver. The feeder would dock and couple to the liner, and then complete the inflight-transfer operation by exchanging payloads (passengers, baggage, fuel, supplies, and flight crews if appropriate) with the liner. It would then undock and descend to a landing at city B, where it would be made ready for another feeder cycle.

During the transfer process, most of the passengers on the feeder from city A would transfer to the liner and continue westward with the liner to a variety of destinations served by the liner; those few passengers from city A whose destination is city B, however, would remain with the feeder and continue to city B. Of the passengers on the liner, some would have destinations at city B and so would transfer to the feeder for landing, while most would continue with the liner to other cities farther west. (To avoid the possibility of confusion, it should perhaps be pointed out that those passengers on this westbound liner who had been scheduled to land at city A would by this time have disembarked on an earlier feeder bound for city A.)

In this particular transfer operation, then, there are four distinct categories of passengers, representing four different sets of passenger trip paths. Only one of these categories (city A to city B) corresponds to the flight path of a particular airplane; each of the other categories represents a collection of trip paths that can conceivably be as large as the number of passengers involved. The inflight transfer scheme thus serves to decouple the passenger trip path from the airplane flight path. In terms of the fundamental transportation-system characteristics, the decoupling function is perhaps the most significant change associated with inflight transfer. The scheme introduces the possibility of mixing the passenger trip-paths during the flight in a manner analogous to the mixing of transfer traffic which is accomplished at the hub terminals in the existing system. The liner therefore serves, in this sense, as a traveling "flying airport".

The feature of mixing the trip paths in flight makes the Relay system extremely versatile, compared to the existing system, in terms of the number of trip paths which can be served at any given frequency, for a given number of airplanes of given size. Because every passenger on the liner has access to any of the feeders which dock

with the liner during his trip, any particular passenger might be traveling between any combination of points of origin and destination served by the liner. An inflight-transfer system of this kind would therefore permit nonstop transcontinental airline travel to originate from and terminate at secondary airports. In this way, primary service could be brought to the smaller airports within the large metropolitan area and also to the local airports in smaller cities which are now served by connections through the metropolitan hub terminals.

### Relay-System Vehicle Design

At the present stage in the development of the Relay system it is clearly premature to be concerned with system details at the level of a careful preliminary design of the system vehicles. Nevertheless, if the preliminary systems-study is to be meaningful, it is necessary to develop some insight into the general requirements for the vehicles and the manner in which the vehicle characteristics influence the performance of the system. To this end, a broad conceptual design study has been made in an attempt to establish "representative" designs for the liner and feeder vehicles. It should be understood that no attempt has been made to optimize these designs from the points of view of either the Relay system or the vehicles themselves, or to make detailed performance analyses on the representative designs. It is believed, however, that the designs are self-consistent and reasonable in the context of the technology expected for the 1990's, and that the Relay system could be made to work well with vehicles very similar to those represented here.

### Liner Design

The representative design for the Relay-system liner module is shown in the sketch of Figure 6. This is an unswept, constant-section, all-wing airplane which has a design capacity of 800 seats. It has a 320-foot span, an 80-foot chord, and a maximum thickness of twelve feet (thickness ratio of 15 percent). The nominal cruise speed has been set at  $M = 0.75$ , which is comfortably below the drag-rise Mach number for this design. The nominal cruise altitude has been taken to be 40,000 feet, which is a compromise between the requirements for accessibility for the feeders (which favors a lower altitude) and for the most efficient cruise (which favors a higher altitude). In operation, the liner altitude would probably vary considerably, depending on the number of feeders to be served along a given portion of the route.

The feeder docking port in this liner-module design is on the spanwise centerline of the module, at the aft end of a short fuselage. In the docking position, the nose of the feeder is joined to this docking port, as shown in the sketch. This "nose-to-tail" docking configuration was chosen for the reason that it gives a minimum of drag for the coupled vehicle pair. Since the liner module must spend a significant fraction of its time coupled with the feeder aircraft (about a third, in the nominal case of U.S. domestic travel in these representative vehicles), the drag of the combination is important. As would be expected,

retractable fairing to avoid the unacceptable base drag on the docking-port cross section. The forward end of this fuselage houses the pilot's station.

Because of the fact that the liner module must be able at various times to operate either as a single-module liner without laminar-flow control, or as a portion of a multiple-module liner with laminar-flow control, the thrust required under various conditions can vary widely, almost by a factor of ten. To accommodate the variable thrust, the module design incorporates four turbofan engines housed within the aerodynamic profile of the thick wing, with retractable "sugar-scoop" inlets in the lower surface of the wing, and retractable clam-shell fairings at the aft ends of the engines along the trailing edge. Each engine can thus be run whenever required and then shut down, with essentially no penalty in configuration drag. Furthermore, since the liner span is large, the performance penalty associated with the small weight of the extra engines is very small.

The 320-foot span of the liner module was considered to be about as large as is practicable, considering the requirement to land safely under emergency conditions. This span is, of course, much greater than available runway widths; it could be accommodated under emergency conditions at most airfields, however, if the module makes use of air-cushion landing gear. With an appropriate system of deployable air-cushion "curtains," the system could utilize almost the entire wing area of the underside of the wing, and be "blown" by the deflected exhaust of the engines. Additional braking capacity could be provided by means of drogue parachutes. An air-cushion landing system of this kind could satisfy the emergency landing requirements with an increment in operating weight which is only a few percent of the vehicle weight required for air-borne operation alone.

Because the liner module can be refueled in flight every few hundred miles, it can operate with an extremely low weight of onboard fuel, hardly more than the reserve fuel required for emergency conditions. The low fuel weight gives the module an unusually low gross weight for an aircraft of this size; preliminary estimates indicate that a gross weight would be about 800,000 pounds. With this low weight and large wing area, the wing loading would be extremely low by the standards of conventional transports - about 30 pounds per square foot. The low wing-loading appears unfortunate at first glance, (because the lift-to-drag ratio could be improved somewhat if the wing loading were greater), but it seems to be an inescapable result of the low weight and the requirement to have a large cabin area for passenger comfort in this advanced system.

Even with the low wing-loading, however, the all-wing configuration is much more efficient than fuselage configurations for aircraft of this size: the structural weight is lower for a given span, so that large span can be achieved at acceptable weight; and the "wetted surface" friction drag is low, since the ratio of external surface area to usable cabin-floor area for this design is less than half of that for the current widebody transports. The large wing area is also a defi-

nite advantage for the emergency landing capability. If the liner can, in fact, be equipped with laminar flow control, the configuration would be extremely efficient by conventional standards: the cruise drag per seat of the five-module liner would be about ten percent of that for current transports.

With the given dimensions and seating capacity, the liner module would also be an extremely comfortable vehicle in which to cruise long distances. The usable passenger-cabin area for this design (exclusive of the space required for baggage, equipment, and passage ways to accommodate the inflight transfer system) would be about fifteen square feet per seat, which is about double the current widebody standard. Since most of the Relay-system traffic will be direct and nonstop, it is believed that the comfort of the spacious accommodations would make higher cruise speeds unnecessary (and undesirable if the cost is a reduction in comfort or service).

The interior volume of the all-wing liner design must incorporate special provisions for carrying the internal pressure load, if a large weight penalty is to be avoided, because of the general "non-circular" shape of the aerodynamic enclosure. The preferred means of accommodating the internal pressure load is to use a separate pressure-resistant structural membrane which is supported inside the basic wing structure. The membrane can be designed to carry the pressure loads in tension by giving it the general shape of a "multiple-bubble" airmattress. The membrane geometry could take the form of a series of intersecting cylinders with chordwise axes, with the internal ridges (at the intersections) supported by "drop-cords" and "tension curtains" in the tradition of flexible airship structures. The drop-cords would probably take the form of stiff floor-to-ceiling posts, similar to those used as hand-holds on busses and trains. The interior volume of the liner would therefore have the appearance of a sequence of large, continuous, theater-size bays, separated by chordwise walls which act as shear-resistant structural frames (i.e. ribs). The structure to carry the internal-pressure loads in this way could be provided at a weight penalty which is almost negligible - in the neighborhood of two percent of the module gross weight.

The opportunity to specialize the liner design is thus seen to be essential to the Relay system concept for several reasons: it allows the liner to be aerodynamically and structurally efficient, mechanically simple, and lightweight; it also allows the liner to be extremely large, as desired for the purposes of the "flying airport" operation. In addition, the multiple-module configuration incorporates a high level of redundancy which, if properly taken account of in the vehicle control-system design, can provide a very high level of fail-safe system reliability.

#### Feeder Design

The representative design chosen for the feeder aircraft is a relatively conventional short-haul transport with the fuselage modified as required to accommodate the special Relay-system requirements for the docking and transfer opera-

tions, as indicated in the sketch of Figure 6. The design would use high-bypass-ratio turbofan engines with a relatively high thrust-to-weight ratio, together with a relatively low wing-loading, to achieve excellent performance in takeoff, climb, and landing.

The nominal capacity of the representative feeder design is 200 seats, or one-fourth of the nominal capacity of the representative liner module. This capacity is believed to be a reasonable compromise between the requirements for airports of various sizes, and appears to be compatible with the general requirements of the inflight transfer system. Other feeder sizes are possible, of course; an operational system would probably make use of several derivative designs of different sizes. The use of smaller feeders for secondary airports would allow an increase in the frequency of service (in general), but would also necessitate more frequent docking with a liner of given size. The feeder size is constrained to some extent, however, by the requirement to be compatible with the docking port of the liner module. Eventually it may be possible to use more than one size of docking port, but no completely satisfactory approach has been uncovered as yet.

The nose-to-tail coupling arrangement is preferred over various other arrangements which have been considered, for reasons of stability and aerodynamic drag in the coupled configuration. This arrangement also has the advantage that it provides a straight-through, floor-level transfer passageway, as desired for efficient transfer operation. As would be expected, it requires that the pilot's station be elevated above the passenger cabin in the same manner as current transports with nose-loading capability.

The feeder performance estimates used in the present study were taken from a study of turbofan-powered transports with low wing loading (Ref. 6). The family of aircraft developed in that study had characteristics which were very similar to those required by the feeder aircraft, in that they were optimized for short hops of about 250 miles, and were designed for short-field capability. The low wing-loading aircraft made use of active gust-load-alleviation systems to improve ride quality and reduce the gust-load penalty on wing weight. The study considered a matrix of aircraft sizes and FAR field lengths, and examined sensitivities to changes in the various design parameters. Thus while none of the designs exactly matches the nominal feeder design used here, the study provides an excellent basis for choosing the nominal feeder-design parameters and for estimating the nominal performance, insofar as the purposes of this broad conceptual-design study are concerned. The feeder performance estimates were made for a wing loading of 75 pound per square foot and a thrust-to-weight ratio of 0.31 (sea-level static).

The feeder aircraft must carry fuel to the liner, in addition to the fuel required for their own mission plus reserves. Because of the extremely high efficiency of the liner, however, the liner fuel required per seat for the nominal 900 nautical mile trip is only about a third of that required by the feeder for its short hop. The total fuel load on the feeder at takeoff is therefore very small: less than fifty pounds per seat (depending somewhat on the liner configuration and

route parameters), or some five percent of the takeoff gross weight. The fact that the feeder fuel load is low, combined with its excellent terminal-area performance, should help to make it an extremely safe vehicle for high-density terminal-area operation. The feeder capabilities in this regard represent a dramatic improvement over the large, conventional transports which carry the medium- and long-range traffic in the existing system.

The most important aspect of the feeder performance, insofar as it affects the normal operation of the Relay system, is the climb performance. The feeder climb characteristics account for a large fraction of the system fuel burned (about half, in the nominal case), about half of the flying time in the feeder cycle, and almost half of the total feeder trip distance. For this reason, the optimum feeder design would be specialized for climb performance, with near-minimum climb fuel.

The climb qualities of the feeder, as well as other aspects of the terminal-area performance would be improved significantly if the design could utilize turboprop propulsion, instead of the turbofan engines used in the reference design. According to recent studies (Ref. 7), the use of advanced-design turboprop propulsion has the potential of decreasing the fuel consumption of short-range transports by some thirty to forty percent, which would benefit the Relay-system fuel consumption substantially. In addition, the propeller design would have better short-field performance and would be quieter in the terminal area. It would therefore be more readily accepted at small local airfields in suburban areas.

The use of turboprop propulsion for the feeder aircraft is in many respects analogous to the use of laminar-flow control for the liner. The propeller system is of greatest value in the terminal area and in climb; in high-speed cruise its value is perceived as marginal because the fuel saved may not offset the increased system weight and maintenance associated with the gearing and pitch-change mechanisms. For the specialized feeder aircraft, however, the design is freed from the requirements for long-distance cruise, and the potential benefits to the system are increased. Once again, these benefits are made possible by the opportunity to specialize, which is afforded by the inflight transfer scheme.

### Fuel Productivity

The overall fuel performance of the system, under the assumptions discussed above, is shown in possible, of course; an operational system would Figure 7. The curves show the fuel productivity, in seat-miles per gallon, of various Relay-system configurations, and of a conventional widebody transport, as a function of length of passenger trip. For the conventional transport, the trip length is, of course, identical with the range of the airplane; the fuel required to fly a certain distance can be determined by the standard performance-calculation methods. The fuel productivity is a weak function of range, typically having a maximum of about sixty to seventy seat-

miles per gallon at about 1500 miles, and falling off by some ten or twenty percent at maximum range.

The fuel productivity variation for the Relay system has a much different character, primarily because the cruise-vehicle efficiency is so much higher than that for the conventional feeder used for takeoff and landing. Aside from the relative efficiencies, however, the curve has a different character because the rate at which the liner uses fuel is essentially independent of the length of passenger trip: since the liner is refueled frequently inflight the weight of fuel onboard remains essentially constant; furthermore, the fuel burn rate is so small that even for trans-ocean flights without refueling the weight change would be only a few percent of the gross.

The constant value of 700 seat-miles per gallon shown for the five-module LFC liner was calculated for the representative design, assuming essentially full laminarization. This value is believed to be achievable in operation for the design considered. Higher values could be achieved if the system so demanded, by making the span larger or by increasing the seating density in the liner cabin. The point shown for the feeder is at fifty seat-miles per gallon, which is essentially on the conventional transport curve at a range of about 250 miles, for a total of five gallons per seat for the complete feeder-cycle trip. This value represents the minimum fuel associated with a trip on the Relay system.

The fuel required by the Relay system to carry a seat over a trip of a given length can be computed simply by adding the fixed value of five gallons of fuel for the feeder to the fuel required for the given liner configuration to travel the given distance. Plotted as a function of trip length, the fuel productivity for the combined system would have the nature of the curves shown in Figure 7. The shaded area shows a range of fuel productivity for the system, the upper bound corresponding to the fully laminarized five-module liner with 700 seat-miles per gallon, and the lower curve corresponding to a large-span "turbulent" liner design with three times as much cruise drag per seat.

As would be expected, for short ranges the system fuel productivity is close to that associated with the feeder itself; for longer ranges the fuel productivity increases toward the value for the liner alone. For trip lengths of about 1000 miles, under good conditions, the Relay system should be able to provide almost three times the fuel productivity of the existing system. For longer trips, the productivity increases steadily, approaching a factor of ten better than conventional transports for very long trip lengths. For trips of short and medium length, most of the fuel is burned by the feeder; consequently, the use of turboprop propulsion for the feeder would improve the fuel productivity of the system by almost fifty percent for the shorter trips. For a trip length of 1000 miles, the fuel productivity of the Relay system with LFC liners and turboprop feeders would be at least four times as great as that of the existing system.

The fuel productivity calculation also shows that substantial savings in fuel are achievable

with "turbulent" cruise airplanes without laminar-flow control, strictly through the reduction of drag by the use of large span. Furthermore, the various operational advantages of the Relay system can be achieved independently of fuel productivity. Thus, while laminar-flow control would provide substantial improvements in the aerodynamic efficiency of the cruise vehicle, and would therefore make possible improvements in both fuel productivity and passenger comfort, the Relay system should not be considered as being ultimately dependent on the successful development of high-Reynolds-number laminar-flow-control technology.

### Interior Logistics

Because of the fact that the Relay system performance is critically dependent on the performance of the interior-logistics system for handling passengers, baggage, and cargo, a considerable amount of effort has been devoted to this subject in the conceptual development of the overall Relay system. While space does not permit a detailed discussion of the interior-logistics system here, it is important to the understanding of the concept that the principal features of the system be considered in some detail.

The nature of the Relay-system operation obviously requires special means of guiding the passenger through the complex and confusing sequence of decisions concerning where to sit and when to move within the very large, continually changing modular passenger cabin. This requirement is strengthened by the consideration that many passengers will be understandably anxious about missing the feeder connections at their destinations. For these reasons, it is believed that it is essential to provide a passenger-handling system which operates by moving the passenger automatically. The passengers would thereby be relieved of the responsibility to understand and accommodate the feeder schedule for the multiple-module liner. Furthermore, since the nature of the system requires that the schedule be complex, precise, and critically dependent on timing, the system cannot afford to depend on the passenger for this important function. Aside from taking the pressure off the passengers, however, there are other significant benefits which accrue from having an automated passenger-handling system, as will be seen.

### Passenger Handling System

The passenger-handling system as it is now conceived would make use of a system of individual chairs equipped with "ski-lift" suspensions which allow them to be moved as necessary along a ceiling-mounted monorail track by a computer-controlled drive system. When the chairs are not in motion they are clamped to the floor in the manner of conventional airliner seats. Each individual passenger would thus be moved automatically, while remaining in his seat, whenever the system required it. All the vehicles, both liner modules and feeders, would be equipped with the necessary monorail system, and the monorail systems in adjacent vehicles would be connected automatically when the vehicles were coupled together. The system would also be extended to

the loading gates at the feeder airports, to allow the chairs to be removed from the feeder aircraft so as to be left on the ground when not in use.

A Relay-system passenger would enter the system at the feeder airport, after checking his baggage, and be assigned a chair. He would remain with this chair throughout the trip, from the loading gate at the departure airport to the baggage-claim area at his destination airport. The computer system would track the chair through the entire trip, arranging for seating in the appropriate areas of the multiple-module liner, moving the chair at the appropriate times to staging areas, and transferring the chair between vehicles as required. The computer system would therefore have control over the interior logistics of the system, so that the performance of the transportation system would not be sensitively dependent on the understanding and skill of the passengers in the use of the system. The necessary communication between passenger and computer could be provided with a computer link to a small terminal built into the chair. The passenger would thus know what to expect and when to expect it, and would be able to exercise some discretion over where he sits, whom he sits beside, and when he is scheduled to be moved. When the chair is not scheduled to be moved immediately the passenger would be free to leave his seat and avail himself of the amenities provided in the spacious cabin.

The use of computer-controlled chairs in this way would allow the passengers to be moved in rapid and orderly fashion when the operation so requires, as is the case in the interchange between feeder and liner. Since the flow would be both organized and relatively high-speed, less space would be required for passageways and staging areas. Furthermore, there would be a means of controlling the inter-vehicle traffic, which is highly desirable from the point of view of a fail-safe airlock: by keeping the airlocks in the wingtips between modules closed except when a brief "burst" of chair traffic passes through, the problem of airlock reliability in an emergency disconnect from the adjacent module is greatly simplified.

The need for efficient transfer operations places certain requirements on the design of the feeder fuselage. In order to achieve minimum transfer time, and to reduce the effects of traffic surge in the liner, it is necessary that the passenger exchange proceed in both directions simultaneously. Given the relatively large feeder size (including the possibility of stretched versions), the most satisfactory cabin layout appears to be six-abreast seating in three groups of two abreast, with two aisles. This arrangement would allow the seats to be moved in two-abreast strings, with the entire string moved from feeder to liner (or vice versa) as a unit. In this way the actual passenger-exchange operation between feeder and liner could be completed in less than two minutes (assuming the maximum speed of the chair system to be six feet per second), which is well within the system requirements for the inflight transfer operation.

## Baggage Handling System

In the Relay system as it is now conceived, the passenger baggage would be handled by a separate, parallel system in a manner which is analogous to the existing provisions for handling baggage. A separate system is preferred, over a system in which passenger and baggage are carried together, for the same reason that baggage is not carried in passenger cabins today: the volume of baggage carried varies so widely from one passenger to another that it is difficult to conceive of a combined passenger/baggage system that does not suffer from both excess volume for some and inadequate volume for others at the same time. Given the automated sorting and transfer capability demanded by the concept, however, it should not be difficult to provide a system for reliable automated handling of baggage.

In the representative system described here, the general arrangement lends itself readily to a baggage-handling scheme in which the baggage is loaded in the belly of the feeder and transferred to the liner by a conveyor system beneath the floor of the transfer-tunnel "fuselage". In the liner the baggage is handled in a special tubular compartment in the leading edge, forward of the front spar which serves as the major spanwise structural member. This arrangement permits the relatively dense baggage to be placed well forward the cross section (as an aid in controlling the center of gravity), and also makes good use of the relatively unusable forward-compartment volume.

The baggage-handling system in the leading edge would incorporate provisions for receiving, stowing, and sorting the baggage, as well as transferring it between modules so as to accumulate the appropriate load for each feeder. Since the inter-module transfer scheme for the baggage would have the same requirements for airlocks at the couplings as has the passenger-transfer system, the baggage would probably be passed between modules beneath the floor of the chair-track passageway, using basically the same interface design as in the centerline transfer tunnel at the feeder dock.

## Cargo Handling System

Since each passenger "brings his own chair" with him as he enters this logistical system, there is no surplus seating capacity in either the feeder or the liner; the system therefore has to carry only a minimum of unnecessary weight for unused passenger accommodations. More importantly, however, the clear space in the passenger cabin can be used for carrying cargo, with no requirement for the "equipment-change" procedures which are normally associated with multipurpose transports. With proper design, the cargo containers could, in fact, be handled by the same computer-controlled monorail system and logistical procedures as the passengers, thereby allowing passengers and cargo to be carried interchangeably.

While it is obvious that not all air cargo can be carried interchangeably with passengers (e.g. automobiles, cattle, frozen food, etc.), nevertheless much of the current "belly-cargo" traffic could be handled readily. If the passenger-chair

transport system were arranged in such a way that the chairs were normally moved in pairs, side-by-side, then it would be a simple matter to handle a cargo container which is suspended on two standard chair-hangers and which occupies two chair-spaces in the cabin. Such a container might have a volume of about 100 cubic feet and a loaded weight of about 1000 pounds (to be consistent with the usual cargo density of about 10 pounds on cubic foot) in which case it would be able to accommodate a substantial fraction of the cargo now transported in belly containers.

The substitution of cargo for passengers would add about 250 pound of payload for each passenger seat displaced. For an 800-passenger liner, the weight increment could thus be as much as 200,000 pounds. With the large-span multiple-module liners, the drag penalty for the added weight would be small, in the neighborhood of ten to twenty percent of the cruise drag for the fully laminarized condition, depending on the number of modules in the string. The small adverse effect of the weight variation could be further reduced by locating the heavy cargo generally toward the spanwise center of the multiple-module liner, while at the same time keeping the wingtips as light as possible. In this way the weight distribution may be made to approximate the ideal elliptic distribution for the aerodynamic lift, and thereby give near-minimum induced drag without the need to transmit large spanwise bending moments across the intermodule couplings.

For the feeder aircraft, the requirement to substitute cargo for passengers is also easily accommodated by the basic design. The change in payload weight would be somewhat less than a factor of two, and the change in gross weight would be about thirty percent. These variations in weight are small by comparison to the variations among different design conditions (e.g. maximum-range condition compared with maximum-payload condition) which are covered in the design of most transports.

The ability to carry either passengers or cargo or both, with no time lost for equipment change, introduces an important element of versatility in the Relay-system operation. Since most air-cargo traffic can be handled satisfactorily on an overnight basis, the cargo could be "banked" at the airport, to be shipped when cabin space is available. If a substantial fraction of the unused passenger capacity during slack periods could be filled by cargo, the effective load factors for the system could be kept high in spite of the requirement for continuous, all-night operation. Other system benefits derived from the automated cargo handling system can also be envisioned; for example, it could be used as an automated supply system for passenger-support operations such as food services.

#### Airmail System

The automated handling systems which are suggested here the passenger baggage and for cargo also contain all the elements needed to establish a primary distribution system for the Postal Service as a part of the Relay system. Individual packages compatible with the baggage-sorting system, for example, could be shipped separately

as items of air freight. Items could be sent in this way from any one Relay feeder airport directly to any other in a matter of several hours, and in a completely automated fashion, with no hand-sorting and no additional ground-side processing required. The express traffic in the baggage system could also include packages of mail bound for a single post office. Mail which has not been sorted into baggage-sized batches could be put into the system in special cargo containers and processed at a special sorting facility onboard the liner. The mail bound for each destination feeder port could then be accumulated from all the originating feeder ports, placed in the special cargo containers or in baggage-sized packages, and transferred to the appropriate feeder. In this way, nonstop airport-to-airport airmail service could be provided for the entire system at the frequency of the feeder service.

It is worth emphasizing that the ultimate success of any continuously operating system such as the Relay system will depend strongly on the skill with which the various elements of the overall ground-air-ground transportation system can be integrated to take advantage of the system capacity. The ability to carry either passengers, cargo, mail, food, etc. interchangeably, with the same automated interior-logistics subsystems and without expensive configuration changes, could easily make a critical difference in the economic performance of the system. For this reason, the payload-handling elements in the system, including the ground-side subsystems for collection and distribution, must be considered throughout the development as integral components of the overall transportation system.

#### Relay System Capacity

The size of the Relay-system fleet required to satisfy a given demand for airline traffic is not easily estimated in a reliable way because of the lack of experience with continuously operating airline systems. In the existing system, the time-of-day variation of demand strongly influences the airline schedules on the most heavily traveled routes; service is sharply curtailed during the early morning hours because of the lack of demand and the curfews at certain airports. With the Relay system, on the other hand, the requirement for continuous operation makes it important to be able to distribute the revenue traffic as uniformly as possible throughout the daily and weekly cycles.

If the Relay system is arranged so that cargo can be substituted directly for passengers, however, the system can function productively even in the absence of passenger traffic during the early morning slack period, provided that sufficient air cargo can be attracted to the system. In view of the fact that the current cargo traffic amounts to about one-eighth of a ton-mile per revenue passenger-mile and is growing very rapidly, it seems almost certain that by the mid-1990's there will be more than enough cargo traffic to absorb the excess passenger capacity available in the Relay system during the slack periods. If for some reason the cargo operation is not sufficient, however, the variations in passenger demand can be smoothed considerably by adjusting the fare on an hourly basis and by the

use of various strategies to reduce the inconvenience of late-night travel.

Whether the system can operate profitably carrying cargo instead of passengers will depend, of course, on the rates charged. On the basis of current rates, however, the substitution of 500 pounds of cargo for each passenger seat (as discussed previously) would produce essentially no change in revenue. Under these conditions the cargo operation would no doubt be more profitable than the passenger operation. The effective system capacity for passenger traffic may therefore depend on the amount of cargo carried during the day, rather than on the amount of passenger traffic that could be attracted to the wee-hour slack period.

### Liner Seating Capacity

The gross seating capacity, in seat-miles per day, of a liner system with a given number of modules can, of course, be determined immediately by taking the product of the module seating capacity, the module velocity, and the average number of modules in continuous operation. Thus, a single 800-seat module of the representative design would provide a nominal gross capacity of about nine million seat-miles per day. On this basis it would require an operating fleet of about one hundred modules to generate a gross seating capacity equal to the operating capacity currently in use in the existing transport fleet of about twenty-five hundred aircraft. The number of modules actually required to carry the current traffic would probably be somewhat greater, depending on the factors discussed above.

### Feeder/Liner Fleet Mix

The number of feeders required to serve a given fleet of liners operating along a given route depends to some extent on the details of the distribution of the desired feeder service. The ratio of the number of feeders in the fleet to the number of liner modules can be developed analytically, however, for the nominal case in which all the feeders can operate on a uniform schedule (for example, one cycle every two hours). Since the rate at which passengers are delivered to the liners by the feeders must equal the rate at which passengers are carried by the liners, then it can be shown that the feeder/module ratio must be

$$(f/m) = (t_f/t_m)/(S_f k_f/S_m k_m)$$

where  $f$  and  $m$  are the numbers of feeders and liner modules in operation,  $t_f$  and  $t_m$  are the average times for the passenger cycles in the two types of vehicles,  $S_f$  and  $S_m$  are the seating capacities, and  $k_f$  and  $k_m$  are the load factors.

The passenger-cycle times for both vehicles depend on the various parameters which describe the route. For the liner modules, the average time spent is proportional to the length of the average trip. Since the average airline trip in current U.S. domestic travel is about 900 nautical miles, in the well-developed Relay system the average stay time of the passengers on the liners would be about two hours.

For the feeders, the passenger-cycle time is the same as the feeder-cycle time, and therefore must be at least as great as the minimum turn-around time for the feeder. Since the feeder schedules are tied to the liner schedules, however, the feeder cycle time must also be compatible with the schedule time of the liner. If the feeder route is such that it meets the liner at the same geographical point in every cycle (as in the case of a feeder which always operates from the same airport) then the feeder cycle time must be an integral multiple of the schedule period. If the feeder hop takes it downrange along the liner route each cycle, however, the relation is altered by the time increment required for the liner to fly the downrange distance which the feeder has moved since the last rendezvous. Thus, for example, a one-hour liner schedule would require feeder cycle times such as one, two, or three hours, if the feeders did not move along the liner route. However, if the feeders moved downrange along the liner route a distance equivalent to a half-hour of liner travel (here about 215 miles for the 430-knot liner) between successive rendezvous on a given cycle, for example, then the feeder-cycle time for this cycle must be 1.5, 2.5, or 3.5 hours.

The representative design for the feeder airplane can takeoff, climb to altitude, accelerate to cruise speed, then descend and land in a total of about 30 to 40 minutes, depending on the design, while covering a distance of about 150 to 200 miles. If the ground support system were well developed, many of the feeders could therefore meet an hourly liner schedule by taking advantage of the downrange increment. Thus it would be reasonable to assume a 1.5-hour average cycle time for the feeder aircraft under good conditions. For a system which is not so highly developed, a two-hour cycle should be adequate.

To find a representative value for the number of feeders required to serve each liner module, then, we may take the 1.5-hour feeder cycle, together with a two-hour average trip time on the liner and the nominal seating capacities of two hundred and eight hundred seats for the two vehicles. With the assumption that the average load factors for the two systems of vehicles are equal, the above relation for the ratio of the number of feeders to the number of liner modules gives

$$f/m = (1.5/2)/(200/800) = 3$$

This is intended to be a reasonable number for the feeder/module ratio for a well-developed system. At the outset, the average feeder cycle would more likely be two hours, for which case four feeders would be required for each liner module, assuming the route parameters to be as discussed above.

### Fleet Capacity for Primary Service

Another useful relation concerns the size of the liner-module fleet required to serve a given number of airports at the primary frequency of the route. For the purpose of this calculation it is assumed that the system involves only primary airports which are served by both arriving and departing feeders on every pass of a liner in either direction. It can be seen that the rate at

which the system produces distance-weighted traffic flow (passenger-miles) can be determined in either of two ways: by multiplying the number of passengers carried to the liners by the average trip length of a passenger in the system; or by multiplying the average number of passengers on the liner by length of one traverse of the route. If these two quantities are equated, the resulting expression can be solved for the number of modules required as a function of the various route parameters:

$$m = (n S_f k_f d_p) / (S_m k_m d_\ell)$$

where  $\ell$ ,  $m$ , and  $n$  are the numbers of liner, modules, and primary cities on the route,  $d_p$  is the average length of passenger trip,  $d_\ell$  is the length of a one-way traverse of the liner route,  $S_f$  and  $S_m$  are the seating capacities of feeder and module, and  $k_f$  and  $k_m$  are the load factors.

If the liner traverses a route in six hours one-way, for example, and the average passenger trip is two hours, then

$$d_p/d_\ell = 1/3$$

In the case of a route with hourly service in both directions to all the primary cities, a six-hour traverse (twelve-hour round trip) would require twelve liners (i.e.  $\ell = 12$ ). If as before, we take  $S_m = 800$  seats and  $S_f = 200$  seats and assume the load factors to be equal, then these values give

$$m = 1.0 n,$$

which is to say that the number of liner modules required for hourly service on this twelve-hour round trip is approximately the same as the number of primary cities. In the same system, two-hour service to the primary cities would require one module for each two airports (i.e.  $m = n/2$ ).

Each airport which is served at the primary frequency in both directions is, of course, part of the nonstop route network, because of the fact that it is possible either to enter the system or to leave it every time a liner passes the airport. Thus a fleet of twelve five-module liners operating along a given route could provide nonstop hourly service in both directions between every combination of airport pairs in a network of about 60 airports within feeder range of the liner flight path. As discussed above, with an average feeder cycle of one-and-a-half to two hours, this route would require about 180 to 240 feeder aircraft.

It is interesting to compare this Relay system fleet size of 60 liner modules and 180 feeders with the size of the conventional fleet required to provide hourly nonstop service to every combination of airport pairs among 60 airports. Consider a square matrix consisting of a two-dimensional list of  $n$  airports (such as a mileage chart). The number of directional airport pairs in such a matrix is the number of elements in the square matrix minus the number on the main diagonal, or  $n^2 - n$ . This relation is plotted as the upper curve in Figure 8. The difference between the two curves represents the approximate reduction in the number of useful airport pairs due to local "interference" between neighboring airports

which are too close together to warrant use of the system to travel between them. The lower curve is then a reasonable estimate of the number of airport pairs served by the nonstop system at the hourly rate (i.e. at the primary frequency). The figure shows that the 60-module, 180-feeder, 60-airport hourly system serves about 3000 direction airport pairs with hourly nonstop service. By comparison, it would take a fleet of perhaps 8000 to 10,000 aircraft under the existing system to equal this capacity for nonstop service, since the 900-nautical-mile average trip would require a schedule time of at least three hours for the one-way cycle.

### Nonstop-Service Ratio

In practice, of course, a system the size of this 60-module example would not be dedicated to hourly nonstop service among 60 "primary" airports, each having one feeder per hour in each direction, but would be arranged to accommodate a considerably larger number of airports of all sizes, including many "secondary" airports with service at less than the primary frequency. Some of the large primary airports would have enough traffic to fill several feeders for each hourly cycle, while many of the smaller secondary airports would be limited to a few feeders per day.

The passenger traffic between the various airports served by such a system would be of four kinds, as indicated in Figure 9: A, between primary airports; B, from primary to secondary airports; C, from secondary to primary airports; and D, between secondary airports. Of these four categories of traffic, the first three are served in nonstop fashion by the Relay system, although only category A is served at the primary frequency. For category B, the passenger must choose his departure time so as to accommodate the intermittent schedule of feeder service at his destination; for category C, the passenger is restricted in his departure time by the intermittent feeder service, but is assured of access to a feeder for landing at his destination. For category D, nonstop service cannot be assured.

The relative importance of these four categories of traffic is indicated in an approximate way in Figure 9. (It should be noted that the figure is constructed from CAB origin-destination data (Ref. 4) for cities, rather than airports, and so must be interpreted here in light of the intended Relay-system feature of serving several airports in each of the large metropolitan areas.) The dashed curve, which is taken from CAB data for 1976, shows the cumulative fraction of the total originating traffic for the United States as a function of the number of cities (ranked in order of originating traffic) included in the accumulation. For example, the largest forty cities account for about seventy-five percent of the total originating traffic. If these forty cities were served at the primary frequency, the traffic in category A (nonstop at the primary frequency), would account for almost sixty percent of the total, as shown by the lower curve; the traffic in categories B and C (nonstop at a lower frequency), would contribute an additional thirty-five percent, approximately, to give a total (A + B + C) of about ninety-four percent. In this case, then, only about six percent of the traffic would

require stop-overs. The total fraction of the traffic which is nonstop is thus considerably larger than the fraction representing the primary cities alone.

The curves in Figure 9 represent the domestic traffic in the entire United States and thus apply directly to any Relay system development which serves the entire country. They can also be applied with fair accuracy to a single corridor route such as shown in Figure 5, since the distribution of small cities in the U.S. is approximately the same as the distribution of large cities. It should be noted that the curve set in Figure 9 assumes that essentially all the traffic which is not included in the primary traffic is part of the secondary traffic. This assumption gives values for the upper curve (A + B + C) that are somewhat too high, depending on the amount of residual small-city traffic that is not served by the system.

It should be understood that the capacity of the Relay system for carrying traffic with a given number of seats is not claimed to be inherently greater than the capacity of the existing system with the same number of seats. For a given gross seating capacity, in fact, the Relay system loses some passenger-carrying ability from its lower cruise speed and from the substitution of cargo for passengers in the passenger cabin. The fact that the Relay system gains in this sort of comparison from the continuous operation is also clearly not to the credit of the Relay system, for which the continuous operation is a requirement rather than an option; the existing system does have the option to operate continuously, of course, but chooses not to do so.

There are some offsetting gains, however, which can fairly be allowed the Relay system in the comparison of the system effectiveness. For example, feeder operation can be made less objectionable, and may therefore be somewhat less likely to be constrained by curfew. Thus, twenty-four-hour operation may become more profitable than it is now, especially if comfortable nonstop service is available to essentially all destinations, and if cargo can easily be substituted for passengers to maintain high load factors. The elimination of the inefficiencies associated with transfer traffic is also a valid improvement in effective capacity for a given number of seats, since the operation time chargeable to stopovers is substantial. In sum, however, it is not reasonable to suggest that strong arguments can be made either in support of the Relay system or against it on the basis of effective utilization of the transport fleet.

The Relay system does offer great advantages in terms of capacity, however, if the two systems are compared on the basis of equal service, assuming stopovers to be undesirable. The Relay system should therefore be implemented primarily as an adjunct to the existing system, to carry passengers between secondary airports for which the service is now the poorest. In this way, as will be discussed, the best features of both systems would be enhanced to provide both improved capacity and improved service to the overall national air transportation system.

## Relay System Implementation and Development

A major factor in the overall feasibility of a revolutionary concept such as the Aerial Relay System is the ease with which the system can be implemented initially and then developed to the size necessary to make a significant impact. This factor is of primary importance in public transportation systems because of the need to attract investment capital, and because of hazards of organized resistance to the construction of new facilities (and to the discarding of established facilities, where such action is required). As will be shown, the Relay system can be implemented and developed within the existing system, as a separate, complementary, interregional air transportation system operating in parallel with the existing system and making use of existing ground facilities which are now under-utilized. Because of the difficulty and expense of expanding the national airport system, this property is considered to be an important factor in favor of the development of an alternative complementary mode of air transportation such as the Relay system.

### Implementation

In the initial implementation, the Relay system would be set up to operate from existing secondary airports, rather than competing for space at the congested major hub terminals. The implementation would therefore allow an increase in the capacity of the national system with no initial requirement to expand the capacity of the large terminals and with no interference or disruption of service within the existing system.

By bringing secondary airports into the primary air-transportation network, two important functions would be served:

1. The level of service to passengers using the small airports would be dramatically improved, because of
  - a. the elimination of stop-over delays, and
  - b. the increased frequency of service to those airports served by the system.
2. The congestion of the metropolitan hub terminals would be reduced, because of
  - a. a reduction of the direct metropolitan-area traffic which is now served by the hubs, and
  - b. the elimination of regional airline-transfer traffic from the outlying secondary airports.

At the present time, the transfer traffic of 2.b. above accounts for a large fraction of the small-transport traffic at the congested hubs. Furthermore, since each transfer passenger must land and then takeoff again, he occupies seats during two "aircraft operations" on the runway. The reduction of transfer traffic at a given hub would therefore have a strong beneficial effect on the airside congestion at that hub.

The opportunity to improve service to secondary airports, while at the same time reducing congestion at the primary airports, is considered to be one of the major potential benefits of implementing an inflight-transfer system as a means of increasing the capacity of the airport system. This point is important enough to deserve emphasizing: a passenger from an outlying airport who is routed through a congested hub terminal as a transfer passenger requires two "passenger-operations" per trip through the airport. The passenger has no desire to be taken to this crowded airport, and the airport operators do not want him there because his trip wastes valuable operating capacity. On the average, removing this one transfer passenger from the hub system allows the hub to handle at least two additional passengers from the metropolitan area with no increase in the air-side congestion; in addition, it also relieves the passenger of the unwanted stopover. Furthermore, the increment in hub capacity is actually greater than two, since at least one leg of the transfer trip will be made in a small transport which uses the same operation slot as the larger transports employed for interregional traffic. For this kind of traffic, then, the addition of the Relay system would act to increase the overall airport capacity of the national system by an amount which is several times as great as the added capacity of the Relay system itself.

Aside from the effects on long-range traffic, there are also important benefits for short-range traffic. A considerable amount of airline traffic between secondary airports within a given region could be served by the feeders as a direct consequence of their service to multiple local airports. This short-haul service could include "mass-transit" intercity commuter service operating from secondary airports in large cities, as well as low-frequency flights between specific small cities. Because much of this traffic would be within the minimum climb-and-descend range of the feeder aircraft, the cost of providing the short-haul service would add very little to the cost of operating the system. Thus the fares could be set low enough to make this service an attractive addition to the overall metropolitan-area transportation system.

It is important to recognize that these potential increases in the capacity of the air transportation system would be brought about strictly through the development of aircraft and flight equipment only, with essentially no requirement to expand the runway capacity of the national airport system. The development which is required would be directed primarily toward making aircraft and flight systems which are capable of using the existing airports in a more effective manner. For the modern United States, the development of aircraft and flight equipment has consistently proven to be much more straight-forward and easily accomplished than the development of ground facilities; public works projects such as new airports and their supporting public-transportation systems, which typically involve a number of different municipalities and governmental agencies, have become almost unmanageable by comparison with the development of a new airplane. Where new airports are built, however, they would be designed to handle only traffic generated by the community in the neighborhood of

the airport. This factor should help substantially in gaining public acceptance for expanding the airport system in a well-diffused manner. For this reason the potential for increasing the capacity of the air-transportation system without a major effort to expand the capacity of the existing ground facilities is considered to be one of the primary justifications for the development of the Aerial Relay System.

#### Initial Route

The route indicated in Figure 5 would serve as an ideal route on which to implement the Relay system. The route would be set up initially to carry passengers nonstop coast-to-coast in both directions, between secondary airports in each area. By spreading the feeder service at each end of the route over an area perhaps a hundred miles long, it would be possible to bring primary service to a number of outlying districts which now contribute disproportionately to the congestion at the regional hub terminals. In this way the Relay system could begin immediately to augment the capacity of the airport system in each region by an increment which is several times as great as the traffic carried by the Relay system itself, as described above.

A two-way, two-station, "linear" route of this type would allow the Relay system operation to be implemented with a very small initial fleet. If the system made use of vehicles as described above (200 and 800 seats), each liner module should dock with four feeders at each end of the route, in order for the capacities of these two interacting systems of aircraft to be well balanced. For the given liner design the route could be set up as a twelve-hour round trip. If a total of six liner modules were available to be used as separate, single-module liners, then the route could have a two-hour schedule period, and each feeder could meet every liner on every trip. The system would be complete in itself, with the potential for operating the individual aircraft at essentially full productivity, with a total of fourteen airplanes: six liner modules and eight feeders. The route could be started with fewer aircraft, of course, at some cost in productivity.

The fact that all the feeder activity takes place in two areas is also considered to be an advantage for an initial route. This kind of system would be the most forgiving with regard to early system inadequacies and prototype problems, and would allow valuable experience to be gained before the system becomes more complex.

Since cargo and passengers can be handled interchangeably, there is an excellent opportunity to exercise the system at each stage of its development, without risk to passengers, by carrying only cargo. The initial route would therefore probably be operated for some considerable length of time primarily as an air-freight system before initiating routine passenger service.

#### Single-Corridor Route Development

As more equipment becomes available, the initial coast-to-coast route could be expanded, with no interruption in the operation, by simply adding additional capacity to the established route. Additional liner modules could either be added to

the existing liners, to improve the passenger-trip mixing and reduce the fuel consumption, or they could be used to increase the number of liners and thus increase the frequency of service. Additional feeders could be added either at the ends of the route or at cities along the route, depending on the nature of the demand. By the time the fleet grows to be several times as large as the initial fleet, however, the best distribution for the feeders would probably correspond approximately to the distribution of the existing origin-destination traffic along the route.

As might be expected, this coast-to-coast corridor now carries an important fraction of the U.S. domestic airline traffic. On basis of CAB data (Ref. 4); it can be calculated that about forty percent of the total U.S. traffic is carried along this route; another ten percent, approximately, could easily be routed part of the way along this corridor if there were some reason to do so.

The distribution of aircraft seating capacity operating in 1976 between the ten major airports along this corridor in the west-to-east direction is shown in Figure 10. The curve was developed by listing the applicable city pairs, obtaining the daily schedule of aircraft types operating between each city pair, and then adding the appropriate combinations of aircraft capacity to arrive at the total capacity now flying along each leg of the route. Assuming a constant load factor, this distribution corresponds to the daily capacity that would be required for the Relay system to serve these same cities at the same load factor.

It is interesting to observe that the current capacity in operation along this corridor is essentially uniform over the entire length. A uniform distribution of this kind is easily accommodated by the Relay system in its simplest form, because it is compatible with a constant liner capacity. The gross seating capacity associated with having forty modules on this twice-daily route is also shown on the figure. This gross capacity level is somewhat misleading, however, because it neglects the important effects of time-of-day on demand. It also neglects the fact that the current fleet carries belly cargo, which would absorb seating capacity in the liner system. The Relay system fleet required to handle the current traffic along this route might be more nearly 60 modules, operating perhaps as twelve five-module liners. As discussed previously, a liner fleet of this size, together with about 180 feeders, could provide hourly nonstop service to as many as 60 airports along the route.

After some considerable development the single-corridor east-west route might appear as shown in Figure 11. The heavy line represents the nominal track of the liners. The cross-hatched area represents the lateral range (about 120 miles to either side) at which feeder service would be available with essentially no increase in the operating range of the feeders.

It should be remembered that since the ground track of the liner is not fixed, the route could be expanded in a variety of ways: the liners could be flown periodically along a curving route to the south of this nominal track, for example, or a second, parallel route could be established. Another possibility is to split the multiple-

module liners into two parts in order to cover the wider track, and then to rejoin where the track narrows. By exploiting this versatility it should be possible to accommodate a large fraction of the east-west traffic along a belt which might reach a width of six hundred miles or more, with essentially no penalty in operational effectiveness.

#### Inflight Route Mixing

As the development of the Relay system continues, the route system would be expanded by establishing additional routes to bring other population centers into the system. In order to take advantage of the ability of the system to mix the passenger trip-paths, it would be desirable to arrange the routes in such a way as to allow passengers to transfer inflight between routes. This inflight route-mixing feature could be provided by exploiting the wingtip-coupling capability of the liner modules: the routes could be arranged so as to allow the liners to couple together or uncouple, where routes converge or diverge, or to exchange modules where routes intersect.

The ability of this feature to enhance the performance of the transportation system is indicated in Figures 12 and 13. Figure 12 depicts a grid of liner routes, with one representative three-way intersection shown at expanded scale. The enlarged view shows the tracks of six individual modules (or groups of modules) which have the capability of uncoupling, mixing, and recombining routinely. These six modular groups initially form three liners converging on the intersection point from the north, east, and west. As the liners approach the intersection (maintaining appropriately tight schedules) the modules separate and fly in such a way that one part of each of the arriving liners turns and leaves the area along one of the other two tracks. This maneuver acts to mix the passenger volumes of the liners on the different routes, thereby extending the various inflight-transfer-system economies (as discussed for the single-corridor one-dimensional route) to the two-dimensional grid route.

The system enhancement provided by the inflight route mixing is indicated in Figure 13, which shows two such three-way intersections, one at each end of north-south leg of the route. As in the previous figure, the tracks represent separable portions of liners: individual modules, or groups of modules, that can separate, fly independently, and rejoin other modules. The dotted path represents the trip path of a passenger traveling from the Southwest to the Northeast on a sequence of Relay-system routes which exploits the route mixing feature. The trip takes the passenger through the first intersection on a module traveling north, but which is scheduled to turn west at the second intersection. At some point on the northbound flight between the intersections, however, the passenger is transferred within the liner from one modular group to the other (as indicated by the circle) and so arrives at the intersection on a module scheduled to turn east. He thus completes his trip in the eastbound module.

It is interesting to observe that this passenger makes the last half of his nonstop trip on

an airplane that was perhaps a thousand miles away when he began his trip; furthermore, the airplane which carried him initially is perhaps a thousand miles away when he lands. It is apparent from this example that an air-transportation system designed to exploit inflight transfer with route mixing has the potential for being extremely versatile in terms of the availability of nonstop travel for any given number of vehicles in the system.

### Route Network Development

If enroute mixing feature of the Relay system concept works as advertised and is developed adequately, it would become possible to implement still a higher level of organization to exploit inflight transfer. It is conceivable that a system of intersecting liner routes could be set up in such a way that liners moving along these routes would meet at each intersection to exchange modules. If the system covered the United States with a sufficiently fine grid, it would become possible to travel nonstop on a Relay liner between virtually any two airports having moderate levels of feeder service. Since the feeder could easily be designed to operate from short runways, it is possible to expand by a large factor the number of airports served by the primary airline system. The system could eventually be extended to include even the widespread network of small air fields which now handle only general aviation traffic.

A little reflection suggests that such a grid of intersecting routes must form a uniform, regular pattern if the system is to be appropriately synchronized to permit regularly scheduled rendezvous among a fleet of vehicles moving at essentially constant speed; in other words, the links along the grid must require a uniform time interval for transit between intersections. The type of grid shown in Figures 14 and 15 was developed as a result of an investigation of a variety of grids of different geometries and interval sizes, and is believed to represent a reasonable extension of the inflight-transfer concept as it is now understood.

While space does not permit a detailed discussion of the mechanics of the triangular-grid route network, it should be pointed out that the fully developed system would always have one liner with at least three modules moving in each direction along each link, timed in such a way that all the liners in the system are scheduled to reach the grid node-points simultaneously. Shortly before the rendezvous time, then, there would be six liners with a total of eighteen modules converging on each node point in the grid. At the appropriate time, each liner would split into three modules (or groups of modules); one of these would turn sixty degrees to the left, one would continue flying straight, and one would turn 60 degrees to the right. These eighteen modules would then recombine to form six liners moving away from the node, with each liner preparing to. Each liner in the system would therefore divide and recombine regularly, at the primary frequency of the route network. With this system a passenger could make his way across the grid in any direction by traveling on the appropriate sequence of liner modules, so as to be able to fly

nonstop (and almost directly) between any two feeder ports served by the system. The interchange capability thus gives the two-dimensional-grid route network the same service characteristics as the much simpler one-dimensional single-corridor route.

The triangular-grid network shown in Figure 14 represents about the coarsest useful network of this kind for the United States, given the vehicle characteristics presented previously. The grid is placed on the map in such a way as to allow some loiter time in the vicinities of New York, Los Angeles, and San Francisco, while providing a direct path along the main east-west corridor. The network would have a primary schedule period of about sixty-five minutes for the 430-knot liner design, which is to say that the liner would require sixty-five minutes to fly from one intersection to the next. Since the system requires an integral number of links to span the east-west corridor (five, in this case), a primary period of an even hour is not directly compatible with the five-link grid. The route schedule could be set up on a daily repeating basis by making a minor adjustment at some predetermined time during the early morning hours; for example, twenty-one cycles of sixty-five minutes plus one cycle of seventy-five minutes would provide a twenty-four-hour daily cycle. The extra ten minutes would also provide an opportunity each day to recover some schedule slippage without having to drop a whole cycle.

The sixty-five-minute, five-link grid of Figure 14 would require about two hundred modules to operate as a full network. As discussed previously, this size of liner fleet would require about six hundred feeder aircraft. The capacity of the fleet would be great enough to carry the current domestic traffic in the United States, taking account of cargo and time-of-day requirements. The Relay system would not be used in that way, however, since it would always work in conjunction with the existing system, for which the capacity would simultaneously increase by at least a factor of two (by virtue of the way in which the Relay system eliminates transfer traffic and small transports from the metropolitan hub terminals). The five-link, triangular-grid route network would therefore be adequate for at least a tripling of the domestic airline traffic with no additional runway capacity at the metropolitan hubs.

The eight-link grid shown in Figure 15 represents a fully developed triangular grid system. This grid network would have a primary frequency of about forty minutes. To operate as a full network, it would require a minimum of about 500 liner modules, together with about 1500 feeders, although it would probably have at least half again that many aircraft because of the use of more modules on the busier links. Because of the fact that the ground traffic as well as the air traffic would be diffused throughout the metropolitan areas, the system could be expanded in this form almost indefinitely, so that an increase in the capacity of the overall national air transportation system of a factor of ten would no longer be unthinkable.

The operational control of a system such as the triangular-grid network would present a number of obvious problems which must be solved before

the system can be considered a practical proposition. One obvious problem is the matter of accounting for adverse weather conditions such as the jet stream, which will bias aircraft speeds in one direction over a portion of the network, and tend to distort the grid. Another facet of the weather problem concerns the disruptive effects of local thunderstorms, which can unexpectedly delay feeders and require liner aircraft to depart from the uniform-grid flight path. The problem of feeder delay is, in itself, a primary conceptual stumbling block in the system design; an aborted rendezvous (for whatever reason) would cause the arriving liner passengers, who were scheduled to meet the delinquent feeder, to be stranded onboard the moving liner, from where they are poorly situated to wait for the delayed feeder or its last-minute replacement. Throughout the concept, in fact, the matter of the extremely sensitive dependence on near-perfect timing of large numbers of system elements stands out as a major potential source of operational problems.

If the operational problems of a well-developed Relay system are to be solved in a practical way, it will obviously require high-level systems-management technology, with strong dependence on computer-aided decision-making processes. The problem of the aborted rendezvous could be "solved", for example, by having a spare feeder at each feeder port ready to fly to a rendezvous with the liner, rescue the stranded passengers, and carry them to their destination. It is obvious that the one-for-one strategy for spare feeders is unacceptable, but it is also obvious that some spare capacity would be required if the system is to be at all forgiving with respect to unpredictable failures. The purpose of the high-level systems technology in this situation is to find near-optimum solutions to operational problems such as the aborted rendezvous. Since a problem of this kind cannot be solved in advance, if a near-optimum solution is desired, the system-management process would probably involve a continuing, real-time optimization for the entire system, to the extent that the precise takeoff times and flight paths for the feeders, and the precise times and places for the rendezvous, would not be established and assigned until a few minutes before the event. In this way (or so it would seem at this early stage) the system could make the best use of available spare capacity. If the problem is worked carefully, it may be possible to handle an aborted rendezvous in such a way that the passengers are not even aware of the problem, except perhaps for a slightly longer feeder trip from the liner to their destination airport.

The complication of managing the Relay system, especially in a network as complex as a triangular-grid route system, seems extreme and unrealizable at first glance. It should be remembered, however, that the entire system is actually composed of a somewhat confusing array of relatively simple elements executing simple operations which, taken separately, are interdependent in a simple way. Thus, if a computer-based control system can be devised to direct any one of these operations, then (at least in principle) it simply takes a larger computer to direct a thousand similar operations in an optimum way. While may be argued that operational control of a system this size has never been attempted, it has

to be agreed that (if recent experience is any indication) computer technology is not likely to be a limitation in the development of a system such as the Relay system.

As an exercise in judging the complexity of the Relay system route network, it is interesting to compare the schematic route map of the U.S. domestic scheduled airlines shown in Figure 2, with the triangular-grid systems shown in figures 14 and 15. The comparison is not quite fair because the grid systems are shown without the feeder routes. However, for long-distance travel, the relative complexities of the route structures of the two systems is represented adequately. The essential difference between the two route systems, as shown clearly in these figures, is the matter of organization: the existing system, which was formulated before the age of the computer, has a route structure which is distinguished by its ad hoc qualities; by comparison, an advanced system such as the Relay scheme is obviously much more easily organized, and therefore gains an important advantage in potential effectiveness.

The opportunities for air transportation which might be afforded through the extensive exploitation of automated operational control have to date been largely unused. A major guiding principle of the conceptual development of the Relay system has been that there are technical breakthroughs in efficiency and effectiveness to be made by taking advantage of the new high technologies such as automated data processing and systems management. The route network system concept described here is offered as a demonstration that high-level, automated, operational control can provide opportunities to improve the performance of the system in ways which would not otherwise be possible.

#### Summary

The existing air transportation system is limited in capacity by the capacity of the airport system. Because of the severe congestion at the major metropolitan hub terminals, the capacity of the national airport system appears to be inadequate and incapable of expansion. The proposed Aerial Relay system would relieve the congestion at the metropolitan airports by diffusing the traffic more uniformly over the metropolitan areas, performing many of the functions of the airline terminal onboard the special Relay-system aircraft, through the process of inflight transfer. Since there are many under-utilized secondary airports within the metropolitan areas which could be brought into the primary system by this process, the Relay system could be implemented without contributing to the traffic at the major terminals. Furthermore, since the Relay system could be used to reduce the amount of transfer traffic at the hub terminals, it would increase the airport capacity by an amount which is several times as much as the Relay traffic itself. Its implementation could therefore be an extremely cost-effective solution to the airport congestion problem.

The use of inflight-transfer allows the Relay-system vehicles to be specialized to an extent that would be impossible under the existing system. As a result, the system has the potential

for becoming extremely efficient in its use of fuel. For a passenger-trip length of 1000 miles, a well-developed Relay system would require only about one fourth as much fuel per seat mile as the existing system; for longer trips the fuel performance would be even better.

From the point of view of the passenger, the Relay system could provide a spectacular improvement overall service. The system would permit direct, nonstop trips to be made between almost any two airports served by the Relay system, with flights available at the primary frequency of the route, perhaps hourly, both day and night. The system would therefore allow nonstop transcontinental trips to originate and terminate at small, local, secondary airports. Furthermore, the Relay system vehicles would be extremely comfortable by conventional standards, so that long-distance travel should become much more convenient and less demanding.

Because the Relay system would operate from the large number of secondary airports, the system could handle a very large amount of traffic without encountering airport congestion problems. Furthermore, since the Relay system would tend to eliminate the requirement to process small transports at the major metropolitan terminals, the capacity of the existing system could be increased dramatically. The capacity of a national system composed of these two separate but complementary systems could therefore eventually be much greater than the current capacity of the existing national system, perhaps even by a factor of ten.

For its development and implementation, the Relay system would require high-level, automated, systems-management technology which is far more sophisticated than operational control systems in current use. By taking advantage of the potential capability of this new technology in the conceptual design stages, however, it becomes possible to design into the Relay system the potential for transportation-system performance which far surpasses the performance of the existing system or its obvious refinements.

#### Concluding Remarks

It seems apparent that inflight transfer is potentially an extremely powerful technique. With some development, it could provide aeronautics with a variety of valuable new capabilities, making possible an air-transportation system with an efficiency and an effectiveness which far surpass anything possible under the existing system. For this reason, it seems obvious that the technology of inflight transfer will be developed eventually.

At the present time, the national air-transportation system is obviously in trouble, with no hope of being able to accommodate the rapid expansion of unconstrained demand for air travel. An inflight transfer scheme such as the Aerial Relay System could alleviate this inadequacy in an extremely cost-effective and fuel-efficient way, and could be expanded indefinitely to become a high-quality, high-capacity national system. These arguments are believed to form a

compelling basis for making a serious commitment to the timely development of a system such as the Aerial Relay System.

It should be understood that the concept of the Aerial Relay System is being offered here as one possible potential technical solution to the apparently unsolvable problems which the present system faces. It can be expected that other potential solutions will surface as the various new technologies develop and as the problems become more acute. The hope which has motivated the development of the Relay concept is that it will, at the very least, serve to demonstrate that radically different air-transportation-system concepts are possible, and even potentially attractive, in the context of the existing national market and its probable future development. It is further hoped that this demonstration can be made convincingly enough to stimulate discussion about alternative transportation systems in general. To the extent that the concerns about the long-term viability of the present system are valid, it is urgent that the issue of alternative systems be explored as thoroughly as possible, in order that the necessary background technology can be identified and developed before it is too late to be of use in the critical decades ahead.

It is recognized that radical proposals are easily dismissed, and that the effort devoted to them is therefore rarely rewarding except for its own sake. In the present circumstance, however, it appears that the climate for innovation may be the best ever. All the indications are that the demand for air travel is growing so fast that the present system has no reasonable hope of being able to satisfy it. We are thus facing a period in which it will be obvious even to the most skeptical "realists" among us that there is a valuable national and international service to be performed (and a lot of money to be made) by the implementation of an alternative system with the appropriate features.

At this point it seems very likely that, with a modest amount of development on a timely basis, one or more of these advanced alternative transportation system concepts could be made available to serve the next generation of air travelers. If this comes to pass, and if we have done a good job of taking full advantage of the new technological opportunities which are such an essential part of this age, we should be able to enter the twenty-first century with an efficient, high-speed, high-capacity system serving the entire nation with low-cost, long-distance travel at levels of comfort and convenience that transcend anything we might have imagined under the old system.

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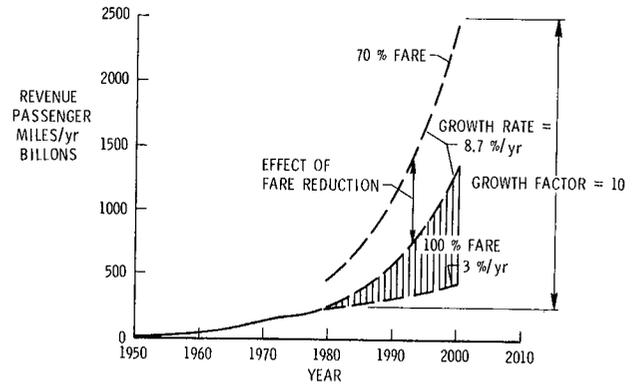


Figure 3.- Projections of U.S. domestic airline traffic.

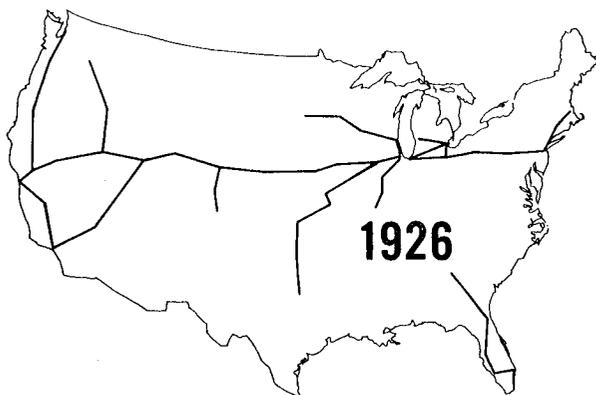


Figure 1.- Early route structure for U.S. airlines.

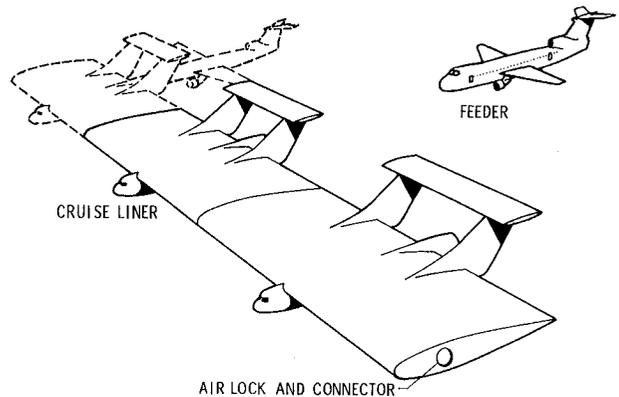


Figure 4.- Basic elements of Aerial Relay System.

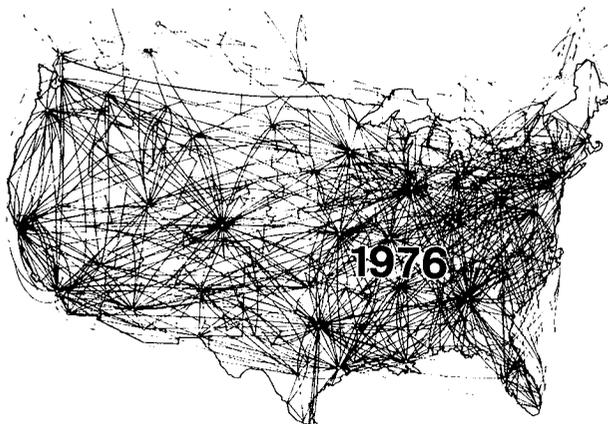


Figure 2.- Current route structure for U.S. airlines.

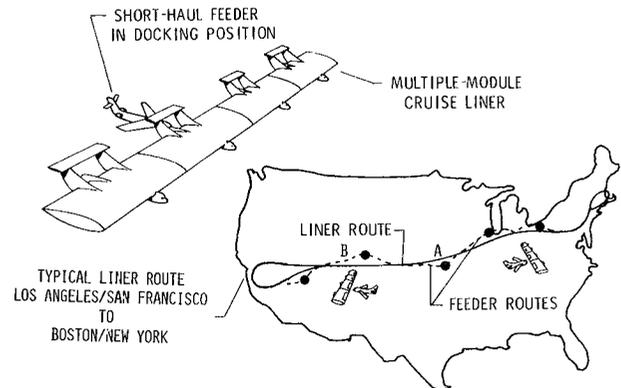


Figure 5.- Basic operation of Aerial Relay System.

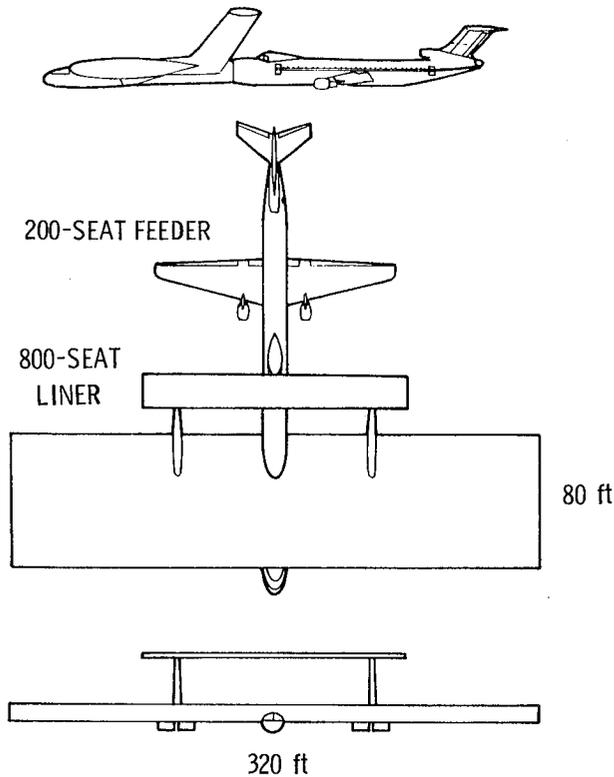


Figure 6.- Representative designs for Relay system aircraft.

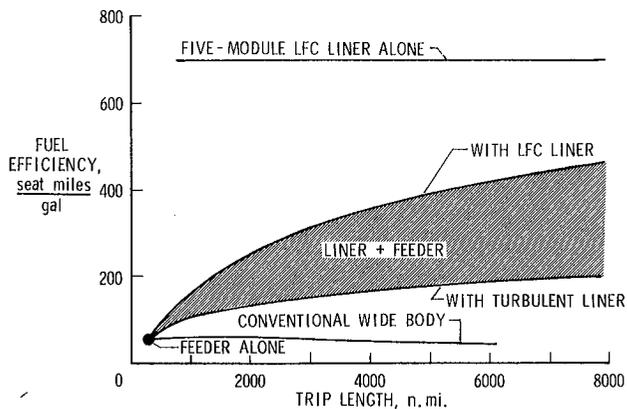


Figure 7.- Potential fuel productivity of Relay system.

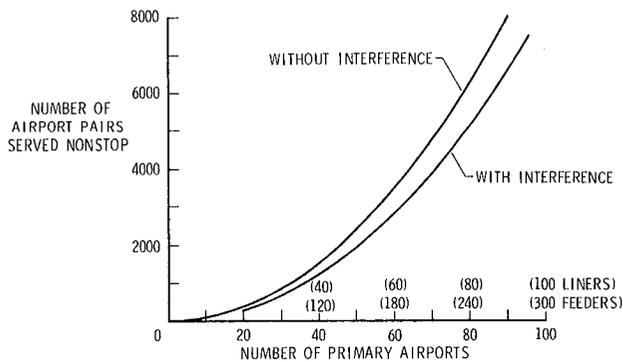


Figure 8.- Capacity of Relay-system fleet for nonstop service at the primary frequency.

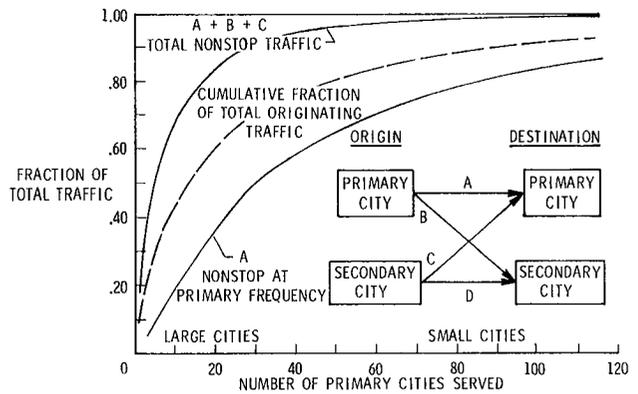


Figure 9.- Fraction of traffic served by nonstop flights.

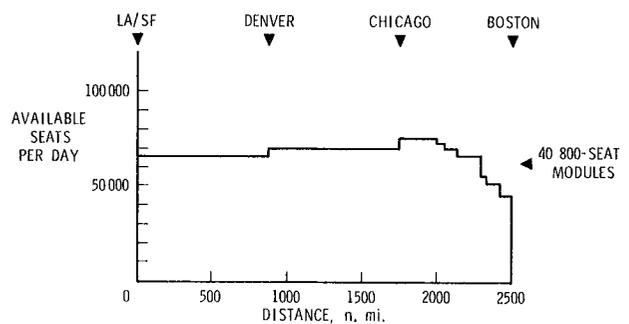


Figure 10.- Current traffic along primary coast-to-coast corridor, west to east.

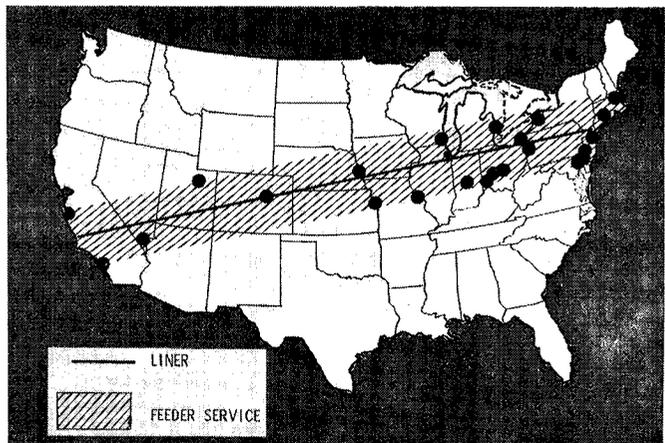


Figure 11.- Single corridor route for Aerial Relay System.

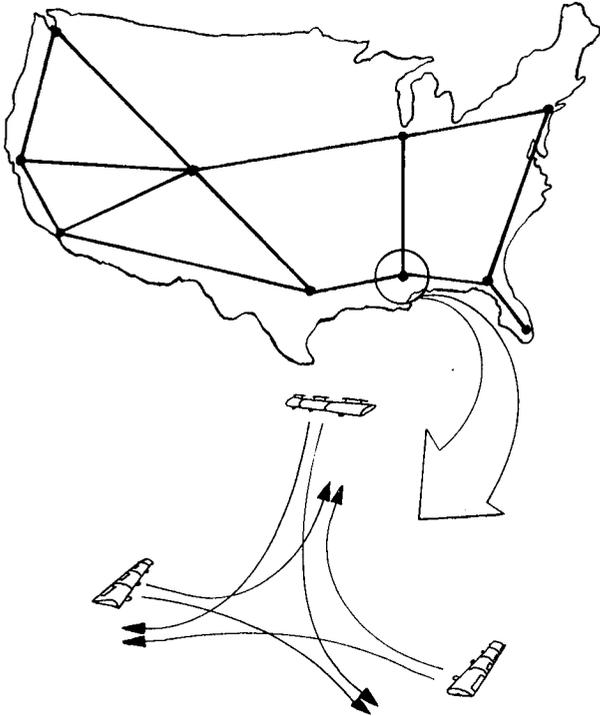


Figure 12.- Inflight route mixing at a single intersection.

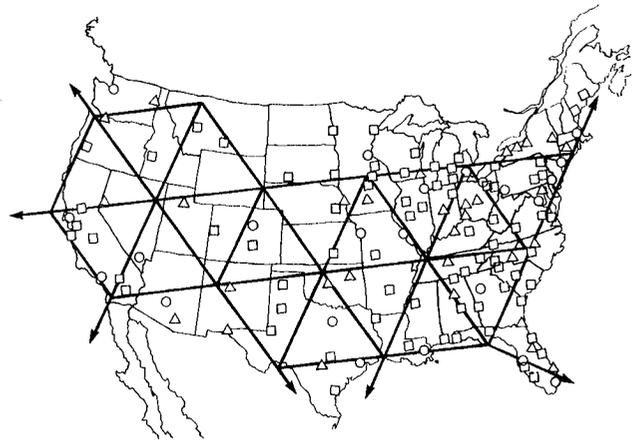


Figure 14.- Triangular-grid route network with five links (5-minute schedule period).

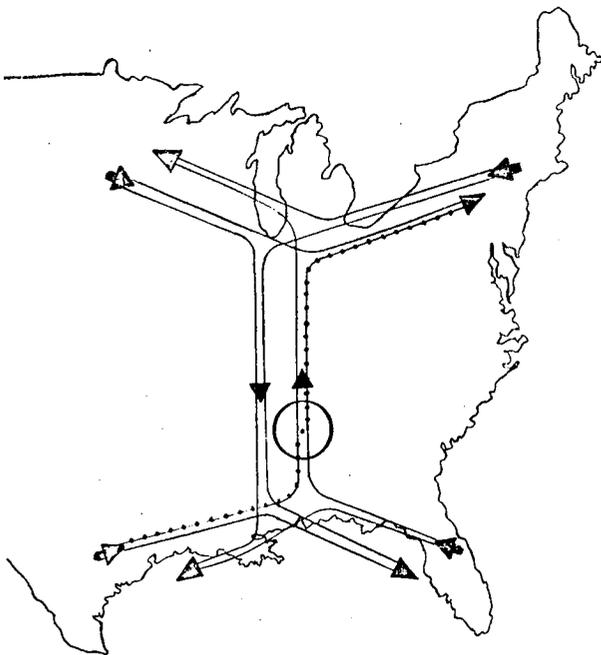


Figure 13.- Inflight route mixing with multiple intersections.

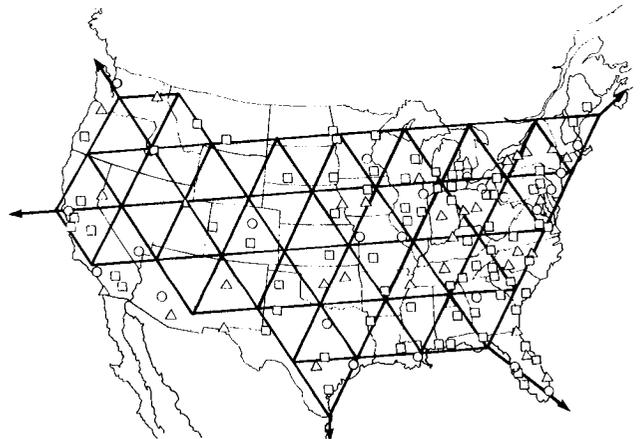


Figure 15.- Triangular-grid route network with eight links (40-minute schedule period).

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16. Abstract  The ability to transfer airline passengers between aircraft in flight, if adequately developed and integrated into the national air-transportation system, could provide significant improvements in transportation-system performance, in terms of airport congestion, fuel consumption, and passenger service. The proposed Aerial Relay System concept, which was developed as a means of exploiting inflight transfer, makes use of large "cruise liner" aircraft which fly continuously along their routes, docking periodically with short-haul "feeder" aircraft for exchange of payloads. The paper describes preliminary vehicle designs for a "representative" system, and discusses the operational feasibility of the concept for the United States in the 1990's.					
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